

# GUT and Supersymmetry at the LHC and in Dark Matter

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## Abstract

Conventional  $SO(10)$  models involve more than one scale for a complete breaking of the GUT symmetry requiring further assumptions on the VEVs of the Higgs fields that enter in the breaking to achieve viable models. Recent works where the breaking can be accomplished at one scale are discussed. These include models with just a pair of  $144 + \overline{144}$  of Higgs fields. Further extensions of this idea utilizing  $560 + \overline{560}$  of Higgs representations allow both the breaking at one scale, as well as accomplish a natural doublet-triplet splitting via the missing partner mechanism. More generally, we discuss the connection of high scale models to low energy physics in the context of supergravity grand unification. Here we discuss a natural solution to the little hierarchy problem and also discuss the implications of the LHC data for supersymmetry. It is shown that the LHC data implies that most of the parameter space of supergravity models consistent with the data lie on the Hyperbolic Branch of radiative breaking of the electroweak symmetry and more specifically on the Focal Surface of the Hyperbolic Branch. A discussion is also given of the implications of recent LHC data on the Higgs boson mass for the discovery of supersymmetry and for the search for dark matter.

Keywords: GUTs , supersymmetry, Higgs boson, LHC, dark matter.

## 1 GUTs and Supersymmetry

*Intoduction:* Grand unification [1–3] for the description of particle interactions is desirable for a variety of reasons (For a review see [4]). We discuss some of the recent developments in unified models which are relevant in view of the hunt for new physics at the large hadron collider [5]. Of specific interest is the gauge symmetry based on  $SO(10)$  [3] which provides a framework for unifying the  $SU(3)_C \times SU(2)_L \times U(1)_Y$  gauge groups and also for unifying quarks and leptons in one generation in a single 16-plet spinor representation. Additionally, the 16-plet also contains a right-handed singlet state, which is needed to give mass to the neutrino via the seesaw mechanism. Supersymmetric  $SO(10)$  models have the added attraction that they predict correctly the unification of gauge couplings, and solve the hierarchy problem by virtue of SUSY. However, SUSY  $SO(10)$  models, as usually constructed, have two drawbacks, both related to the symmetry breaking sector. First, there are two different mass scales involved in the breaking of the GUT symmetry, one to reduce the rank and the other to reduce the symmetry all the way to  $SU(3)_C \times SU(2)_L \times U(1)_Y$ . Thus typically three types of Higgs fields are needed: one for rank reduction such as  $16 + \overline{16}$  of  $126 + \overline{126}$  and then a 45, 54 or 210 for breaking the symmetry down to the standard model symmetry, and a 10 plet for electroweak symmetry breaking. Second, the GUT models typically have the so called doublet-triplet problem where one needs an extreme fine tuning to make the Higgs doublets light. These drawbacks can be corrected in a new class of models recently proposed [6, 7]. Here we will review first this class of models. We will then go on to discuss a variety of other topics which connect high scale models to low energy physics. These include a discussion of supergravity grand unification, the little hierarchy problem, the implications of the recent data from ATLAS and CMS on the Higgs boson. Other topics discussed include proton decay in GUTs, and dark matter. Finally we will discuss a topic which is not necessarily tied to a GUT theory but is of importance and of current interest, which is cosmic coincidence, i.e., the fact that dark matter and baryonic matter are roughly in the five to one ratio. We will discuss a possible solution to this within the framework of a Stueckelberg extension of the standard model and of the minimal supersymmetric standard model (MSSM). We discuss below the topic listed above in further detail.

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*One step breaking of GUT symmetry:* Multiple step breaking requires additional assumptions relating VEVs of different Higgs representations to explain the gauge coupling unification of the electroweak and the strong interactions (for a review see [8]) reducing predictivity, while such an assumption is unnecessary in a single step breaking [6, 7]. In  $SO(10)$  the simplest combination of Higgs representations that can achieve a single step breaking is  $144 + \bar{144}$ . The reason for this is easily understood by looking at the decomposition of the 144 plet of  $SO(10)$  under  $SU(5) \times U(1)$  so that  $\bar{144} = \bar{5}(3) + 5(7) + 10(-1) + 15(7) + 24(-5) + 40(-1) + \bar{45}(3)$ . Here the 24 plet carries a  $U(1)$  quantum number and thus a VEV formation of it will reduce the rank of the group as well as break  $SU(5)$ . Additionally one can obtain a pair of light Higgs doublets needed for electroweak symmetry breaking from the same irreducible  $144 + \bar{144}$  Higgs multiplet. Thus one can achieve the full breaking of  $SO(10)$  into  $SU(3)_C \times U(1)_{em}$  by just one pair of  $144 + \bar{144}$ . Dealing with the 144 representation requires special techniques [9] which utilize oscillator method [10] (For alternate techniques for the computation of  $SO(10)$  couplings see [11, 12]). With a  $144 + \bar{144}$  of Higgs fields the first two generations of fermion masses arise from quartic couplings  $(1/\Lambda)16.16.144.144$  and  $(1/\Lambda)16.16.\bar{144}.\bar{144}$  where  $\Lambda \sim O(M_{Pl})$  and since the effective Yukawas are scaled by  $\langle 144 \rangle / \Lambda$  and  $\langle \bar{144} \rangle / \Lambda$  where  $\langle 144 \rangle = \langle \bar{144} \rangle \sim O(M_G)$  the Yukawas for the first two generation fermions are naturally small. However, additional matter representations are needed for generating large third generation masses. Such additional representations may be 10, 45 or 120 of matter fields. In models of the above type the third generation masses involve very significant representation mixing. It is then possible to modify the conditions for  $b - t - \tau$  unification to occur. Specifically one finds that such a unification can come about for low values of  $\tan \beta$ , i.e., a  $\tan \beta$  as low as 10 in contrast to models where the Higgs doublets arise from the 10 plets and a  $b - t - \tau$  unification requires a large  $\tan \beta$  [13].

*The doublet-triplet problem:* The second problem in GUT theories typically concerns the doublet-triplet mass splitting, i.e., one must do an extreme fine-tuning at the level of one part in  $10^{14}$  to get the Higgs doublets of MSSM light, while the color triplets-anti-triplets remain superheavy. Some possible solutions to the doublet-triplet problem include: (i) The missing VEV solution where  $SO(10)$  breaks in the B-L direction which allows the Higgs triplets and anti-triplets to be heavy while the Higgs doublets remain light [14]; (ii) The flipped  $SU(5) \times U(1)$ ; (iii) The missing partner mechanism, and (iv) Orbifold GUTs [15]. The missing partner mechanism and the orbifold GUTs are rather compelling in that some doublets are forced to be massless. We will focus on the missing partner mechanism [16] and discuss how it works in  $SU(5)$  and then discuss how one can extend to  $SO(10)$ . In  $SU(5)$  the Higgs sector consists of  $50, \bar{50}$  and 75 plets of heavy representations and  $5, \bar{5}$  of light representations. The 75 plet breaks the GUT symmetry, while  $50, \bar{50}$  have the property that they contain a Higgs triplet- anti-triplet pair but no higgs doublet pairs. When mixing is introduced between the light and the heavy sectors, the Higgs triplets-anti-triplets become heavy while the doublets remain light. Thus here one naturally achieves a pair of light higgs doublets.

In  $SO(10)$  the missing partner mechanism is more complex. This complexity arises due to the additional problem of exotics. The reason for this new feature in  $SO(10)$  is due to the light sector which unlike the light sector in the  $SU(5)$  case contains a new array of massless fields which must also be made heavy. One example of a missing partner mechanism in  $SO(10)$  was achieved in [17] consisting of a heavy sector with  $126 + \bar{126} + (210 + 16 + \bar{16})$  of Higgs and a light sector with  $10 + 120$  plet of Higgs. The  $210 + 16 + \bar{16}$  fields are responsible for the breaking of the  $SO(10)$  gauge symmetry. The remaining heavy sector fields, i.e.,  $126 + \bar{126}$  fields do not mix with the  $210 + 16 + \bar{16}$  and do not acquire VEVs., but they play the same role that  $50 + \bar{50}$  play in  $SU(5)$ , i.e., they contain an excess of triplet and anti-triplet pairs relative to the doublet pairs. After mixing with the light fields a careful count shows that there is one pair of Higgs doublets which are left massless while all the Higgs triplets and anti-triplets gain mass. Thus the missing partner mechanism works. More recently several more cases have been discovered [18]. These include one model where the heavy sector is  $126 + \bar{126} + 210$  and the light sector consists of  $2 \times 10 + 120$ , while another model consists of a heavy sector with  $126 + \bar{126} + 45$  and a light sector consisting of  $10 + 120$ . In addition an entirely different array of representations have been found which also lead to the missing partner mechanism. This possibility consists of  $560 + \bar{560}$  plets which constitute a heavy sector and  $2 \times 10 + 320$  plets which constitute a light sector. Here  $560 + \bar{560}$  contains an excess of Higgs triplet and anti-triplet pairs over Higgs doublet pairs which again allows for the missing partner mechanism to work. This is easily seen by decomposing the 560 and the 320 multiplets into their  $SU(5)$  components. Thus  $560 = 1(-5) + 5(3) + \bar{10}(-9) + 10(-1) + 10(-1) + 24(-5) + 40(-1) + 45(7) + \bar{45}(3) + 50(3) + 70(3) + 75(-5) + 175(-1)$  and for the 320 multiplet one has  $320 = 5(2) + \bar{5}(-2) + 40(-6) + \bar{40}(6) + 45(2) + \bar{45}(-2) + 70(2) + \bar{70}(-2)$ . A simple count of the Higgs doublets and triplet-anti-triplet pairs shows that the heavy sector consisting of  $560 + \bar{560}$  has 4 doublet pairs and five triplet-anti-triplet pairs, while the light sector consisting of  $2 \times 10 + 320$  multiplets consist of 5 doublet pairs and five triplet-anti-triplets pairs leaving us one light doublet pair and no light Higgs triplet -anti-triplet pair after mixing of the light and the heavy sectors. The multiplets 560 and 320 have not surfaced in GUT model building before but arise as natural possibilities in the context of achieving a missing partner mechanism

in  $SO(10)$ . The models of the type discussed above have the possibility of accommodating large neutrino mixing angles and also relatively large values of  $\theta_{13}$  as indicated by the recent data from experiment [19]. The detailed implications of these models still need to be worked out.

One possible danger in the missing partner mechanism concerns the possibility that the Higgs doublets may receive contributions of size  $M_G^2/M_{Planck}$  arising from Planck scale corrections. The presence of such corrections would spoil the missing partner mechanism. However, as discussed, e.g., in [17, 20], such corrections can be forbidden by an anomalous  $U(1)$  symmetry. Another issue concerns the nature of the theory above the scale  $M_G$ . Thus because of the large number of degrees of freedom, models of the above type are not asymptotically free above the unification scale  $M_G$ . However, the region above  $M_G$  is the region where gravity becomes strong. In particular this happens when there are a large number of degrees of freedom  $N$  involved. As pointed out recently [21] in this case the effective fundamental scale is reduced by a factor  $\sqrt{N}$  which lies in the vicinity of  $M_G$ . Because of the proximity of the fundamental scale to  $M_G$ , the effect of non-renormalizable interactions would be very significant and must be included above the scale  $M_G$ . Inclusion of such terms would redefine the theory in a significant way above  $M_G$  and the appropriate procedure in this region then is to use here the UV complete theory rather than a truncated version of it.

*SUGRA unification and LHC implications:* In order to make contact with low energy physics one needs to break supersymmetry in a supersymmetric grand unification. It is difficult to achieve such a breaking within global supersymmetry and one must make supersymmetry a gauged symmetry which brings in gravity [22] and thus gravity enters in an intrinsic way into model building. Specifically we need the framework of applied  $N = 1$  supergravity [23, 24] to build models and in particular supergravity grand unification [25]. A broad class of models fall under this rubric. These include mSUGRA (sometimes referred to as CMSSM) [25], and SUGRA models with non-universalities in the Higgs sector and in the gaugino sector (see [26, 27] and the references therein). Non-universalities of soft masses also arise in string models and D brane models (see [28] and the references therein). The parameter space of mSUGRA is well known consisting of  $m_0, m_{1/2}, A_0, \tan \beta, \text{sign}(\mu)$  where  $m_0$  is the universal scalar mass,  $m_{1/2}$ , the universal gaugino mass,  $A_0$  the universal trilinear parameter all taken at the GUT scale, while  $\tan \beta = \langle H_2 \rangle / \langle H_1 \rangle$  where  $\langle H_2 \rangle$  gives mass to the up quarks, and  $\langle H_1 \rangle$  gives mass to the down quarks and the leptons, and  $\mu$  is the Higgs mixing parameter in the superpotential. For non-universal SUGRA models there are additional parameters. For example, for the gaugino sector one can choose different gaugino masses at the grand unification scale, i.e.,  $\tilde{m}_1, \tilde{m}_2, \tilde{m}_3$  for the  $U(1), SU(2), SU(3)$  sectors, and  $m_{H_1}, m_{H_2}$  for the Higgs sector. There are also other mechanisms for the breaking of supersymmetry such as gauge mediation, anomaly mediation and the breaking by an anomalous  $U(1)$  as well as involving mixtures of these such as a mix of gravity breaking and anomalous  $U(1)$  breaking [29]. Comparison with low energy data, of course, requires renormalization group evolution (see, e.g., [30] and for a review see [31] and the references therein) to compute the sparticle mass spectrum. Now the sparticle landscape is rather large [32] and one needs tests at colliders to delineate the nature of soft breaking using experimental data (for a review see [5]) and for related works see [33, 34]). The sparticle spectra can be affected by CP violating effects (for a review see [35]). One of the important signatures for supersymmetry is the trileptonic signal [36, 37]. This signature from the on-shell decay of the  $W^\pm \rightarrow \tilde{\chi}^\pm \chi_i$  at colliders was discussed in [38], and for the off-shell decays in [39] with further work in [40] and in several other papers.

*The little hierarchy problem:* One version of the so called little hierarchy problem relates to keeping  $\mu$  small while  $m_0$  gets large. Using radiative breaking of the electroweak symmetry one can write [41–45] (for related works on naturalness see [46–48])  $\mu^2 = -\frac{1}{2}M_Z^2 + m_0^2 C_1 + A_0^2 C_2 + m_{\frac{1}{2}}^2 C_3 + m_{\frac{1}{2}} A_0 C_4 + \Delta\mu_{loop}^2$ . The case  $C_1 > 0$  is the so called Ellipsoidal Branch. Now in certain regions of the parameter space  $C_1$  can vanish or turn negative. This converts the REWSB equation from an Ellipsoidal Branch to a Hyperbolic Branch (HB). One can further classify the HB region into three separate regions [45]. These are: (i) The Focal Point region HB/FP where  $C_1 = 0$ ; (ii) The Focal Curve region HB/FC: Here  $C_1 < 0$  and two soft parameters can get large for fixed  $\mu$ , and (iii) The Focal Surface region HB/FS: Here  $C_1 < 0$  and three soft parameters  $m_0, m_{1/2}, A_0$  can get large for fixed  $\mu$ . Now from the RG analysis it is possible to write  $C_1$  in the form  $C_1 = (1 - 3D_0)/2$  where  $D_0(t) = \exp[-6 \int_0^t Y_t(t') dt']$  and  $Y_t = h_t^2/4\pi^2$  where  $h_t$  is the top Yukawa coupling and where  $t = \log(M_G^2/Q^2)$ . It is also easily seen from the solution to the RG equations that the RG correction to the Higgs boson mass that couples to the top quark, i.e.,  $H_2$ , is given by  $\delta m_{H_2}^2 = m_0^2(3D_0 - 1)/2$  and is thus related to  $C_1$  simply as  $\delta m_{H_2}^2 \simeq -m_0^2 C_1$ . One finds then that  $C_1$  vanishes for the case when  $D_0 = 1/3$  which also implies the vanishing of the correction  $\delta m_{H_2}^2$ . This is the Focal Point region (HB/FP). Recent analyses of the LHC data within supergravity grand unification with universal boundary conditions show that the HB/FP region is mostly depleted and the bulk of the region which remains lies

in the focal curve HB/FC and focal surface region HB/FS [45].

*The Higgs boson mass:* In SUGRA models at the tree level the mass of the light neutral CP even Higgs boson mass is less than  $M_Z$ . However, it can be lifted above  $M_Z$  by loop corrections (For a review see [49]). Specifically in SUGRA models the light Higgs boson mass can run up to around 130 GeV with  $m_0$  in the TeV region [50]. Recent data gives some positive hints for a Higgs boson mass in the vicinity of around 125 GeV [51] which offers support for the supergravity unified model. We note that a Higgs boson mass in the region around 125 GeV points to a heavy sparticle spectrum specifically heavy scalars some of which could be several TeV in mass (see also in this context [52] where a PeV scale has been discussed). However, many sparticles could still be light, i.e., the light stop and the sbottom, charginos and neutralinos. Further, a gluino mass in the vicinity of a TeV is still allowed [50]. Detailed analyses of the sparticle spectrum and of the Higgs sector require imposition of the experimental constraints. These include the relic density constraint on the neutralino dark matter, the constraints from the flavor changing processes  $b \rightarrow s + \gamma$  [53],  $B_s \rightarrow \mu^+ \mu^-$  [54], from the muon anomalous magnetic moment [55], as well as constraints from the sparticle lower limits from experiment [56]. We note in passing that the Higgs boson sector is affected by CP phases and new detectable phenomena arise due to mixing of the CP even and CP Higgs bosons [57].

*Proton decay:* Another aspect of grand unification is proton decay which is a generic feature of unified models of particle interactions. There are a variety of sources for proton decay. The most generic feature in GUT models is proton decay via the exchange of vector lepto-quarks. The current experimental limit  $\tau(p \rightarrow \pi^0 e^+) > 1.4 \times 10^{34}$  yrs implies a very rough lower bound on the superheavy gauge boson mass of  $M_V > 5 \times 10^{15}$  GeV. Thus proton stability at current levels implies the existence of a very high scale, much closer to the Planck scale than the weak scale. In supersymmetric grand unification further constraints are needed. Thus B&L violating dim 4 operators appear in SUSY, i.e.,  $QLD^C, U^C D^C D^C, LLE^C, LH$ , leading to fast proton decay and their suppression requires R parity. However, even with R parity B&L violating dimension five operators, i.e.,  $QQQL/M_T$ , and  $U^C U^C D^C E^C/M_T$ , are allowed and generate proton decay. Thus dressing loops convert these dim 5 operators to B&L violating dim 6 operators involving quarks and leptons. Further, these dim 6 operators are converted to an effective lagrangian involving mesons and baryons which allow one to calculate proton decay processes such as  $p \rightarrow \bar{\nu}_{e,\mu,\tau} K^+, \nu_{e,\mu,\tau} \pi, \nu_{e,\mu,\tau} \eta, \mu\pi, eK, \mu K$ . A variety of GUT and string models can be tested using proton decay constraints [58]. There is significant model dependence in the predictions of the proton decay modes specifically of the SUSY decay modes. Thus the decay lifetimes depend on the nature of soft breaking which enters in the dressing loop diagrams [59–61]. Additionally proton decay can be affected by: (i) gauge coupling unification which constrains the Higgsino triplet mass; (ii) quark-lepton textures, (iii) FCNC and dark matter constraint, and (iv) gravitational warping effects [62, 63]. Finally we may mention that the accuracy of effective lagrangian approximation which converts operators such as  $QQQL$  and  $U^C U^C D^C E^C$  into lagrangian with mesons and baryons can have an effect on the proton decay life time predictions. Further, predictions of proton lifetime for supersymmetric decays depend significantly on the particulars of the supersymmetric grand unified model. Often a suppression of B&L violating dimension five operators is needed to raise the proton lifetime beyond the current experimental limits. A variety of possibilities exist for such a suppression. These are: (i) The cancellation mechanism [7] which can operate if there are more than one source of Higgsino mediation, (ii) One or more couplings that enter in Higgsino mediated proton decay are naturally suppressed by an internal mechanism, and (iii)  $m_0$  is large and REWSB is realized on the Hyperbolic Branch where large scalar masses consistent with small  $m_{1/2}$  and  $\mu$  are allowed. An example of the cancellations or suppression of Higgsino mediated proton decay occurs in the  $144 + \bar{144}$  Higgs model [7]. Proton decay lifetime has been calculated in the  $144 + \bar{144}$  unified higgs model and the results are consistent with current experiment and allow for the possibility of the discovery of the decay in improved p decay experiments [64]. One important conclusion that one finds in this and other similar analyses is that the discovery of proton decay may be just around the corner and such a discovery may occur even with modest improvements in the sensitivity of proton decay experiment.

*Gauged B-L, R parity and the Stueckelberg mechanism:* As can be seen from the preceding discussion, R-parity (defined by  $R = (-1)^{2S+3(B-L)}$ , where  $S$ ,  $B$  and  $L$  stand for the spin, baryon and lepton numbers, respectively) is an important symmetry in supersymmetric theories and is often imposed on GUT models on phenomenological grounds but it could also be automatic [65]. However, R parity even if preserved at the GUT scale can undergo spontaneous breaking due to renormalization group effects (see, e.g., [66] and the references therein). It is then interesting to ask if the radiative breaking of R parity can be evaded. One possibility is that R parity arises as a remnant of a gauged  $U(1)_{B-L}$ . Thus within MSSM one may have an anomaly free  $U(1)_{B-L}$  by inclusion of right handed neutrinos, one for each generation. Also GUT models such as  $SO(10)$  and  $E_6$  and string models possess

a gauged  $U(1)_{B-L}$ . However, the massless gauge boson associated with a gauged  $U(1)_{B-L}$  must grow a mass to evade generating an undesirable long range force. The simplest way to accomplish this is by the Stueckelberg mechanism. In the minimal  $B-L$  extension of MSSM, one finds that under the assumption of the universality of soft scalar masses, charge conservation and in the absence of a Fayet-Iliopoulos D-term, R-parity does not undergo spontaneous breaking by renormalization groups effect [67].

## 2 Dark Matter

*Dark matter in SUGRA unification:* While in MSSM the LSP with R parity is stable, there is no reason that the LSP would be a neutral particle much less a neutralino. However, in mSUGRA with universal boundary conditions at the GUT scale, the neutralino turns out to be the LSP over a large part of the parameter space under constraints of color and charge conservation. Thus in mSUGRA the neutralino becomes a candidate for cold dark matter. Many extended SUGRA models, i.e., models with non-universalities, also exhibit the same phenomenon. Stringent constraints have been placed on the allowed lower limit of the neutralino mass in MSSM/SUGRA models [68]. An important test of neutralino dark matter will come from direct detection experiments for the search for dark matter which measure the spin-independent neutralino-proton cross section (see, e.g., [69]). The dual constraints from dark matter searches and from searches for supersymmetry at colliders help delineate stringently the parameter space of models (see, e.g., [70]). Recent experiments have made significant progress in increasing the sensitivity of experiments for this cross section (see, e.g., [71]). Further, some recent experiments have indicated the possibility of the spin-independent cross section as large as  $10^{-40}\text{cm}^2$  in the low mass neutralino region as low as 5-10 GeV [72]. However, while a low mass neutralino, as low as 5-10 GeV, is allowed by REWSB, the constraints from WMAP, from  $b \rightarrow s\gamma$  and from  $B_s \rightarrow \mu^+\mu^-$  essentially eliminate this region of the parameter space. Further, new stringent constraints on dark matter arise from the recent data on the search for supersymmetry [73–76] and for the search for the Higgs boson [51]. In [50] an analysis was carried out including the lower limit constraints on sparticles masses and also restricting the Higgs mass range to 123 GeV to 127 GeV which appears to be the prime region for the discovery of the Higgs boson in view of the recent LHC data [51]. In this case after the imposition of the radiative electroweak symmetry breaking, relic density and the FCNC constraints one finds that essentially all of the mSUGRA parameter points that give a 123 – 127 Higgs boson mass produce a proton-neutralino spin-independent cross section that lies just beyond the most recent experimental limits from the XENON collaboration [71]. However, it is very encouraging that most of this region would be within the projected reach of XENON-1T [77] and SuperCDMS [78].

*Cogenesis:* Another interesting aspect of dark matter concerns cosmic coincidence, i.e., that the baryonic matter and the non-baryonic dark matter are of the same size, and more precisely [79]  $\Omega_{DM}/\Omega_B = 4.99 \pm 0.20$ . The above appears to indicate that these two types of matter are somehow related and have the same origin. Though the topic is outside the main theme of this talk, it is of current interest and we give a brief discussion of it here. Thus there is the suggestion of the so called asymmetric dark matter which proposes that dark matter could be created by a transfer of a net  $B-L$  asymmetry created in the early universe to some standard model singlet which would be the dark matter candidate [80]. There are two main issues that need attention here. The first is how one may carry out such a transfer and the second how the dark matter produced by thermal processes (symmetric dark matter) is dissipated. Regarding the first item, a transfer of  $B-L$  can occur via interactions of the type [81]  $\frac{1}{M_a^n} O_{DM} O_{asy}^{SM}$ , where  $O_{asy}^{SM}$  is constituted of only the standard model particles and carries a net  $B-L$  quantum number and  $O_{DM}$  is constituted of dark matter fields and carries the opposite  $B-L$  quantum number. Regarding the second item, one needs to demonstrate in a quantitative fashion that the symmetric component of dark matter is efficiently annihilated. We do not speculate on how the  $B-L$  asymmetry originates and simply assume that it exists. Assuming a pre-existing  $B-L$  the analysis then revolves around a transfer of the  $B-L$  from the visible to the dark matter sector. A common assumption is that the  $B-L$  transfer occurs at a temperature  $T > T_c$ , where  $T_c$  is the temperature of electroweak phase transition, and also  $T > T_{sph}$ , where  $T_{sph}$  is the sphaleron temperature (although a variety of other possibilities have also been explored). There are various possibilities for  $O_{asy}^{SM}$  and for  $O_{DM}$ . Thus, e.g.,  $O_{asy}^{SM}$  could be  $LH, (LH)^2, LLE^C, LQD^C, U^C D^C D^C$  while  $O_{SM}$  could be  $\psi^k$  where  $k > 2$  where  $\psi$  is the dark matter particle. In the specific analysis of [82] interactions involving the leptonic doublets are considered and no flavor mixing is assumed in this sector so  $L_i$  are separately conserved. Further, in SM we can gauge one combination of  $L_i - L_j$  (or  $B-L$ ) [83] which we choose to be  $L_\mu - L_\tau$ . The gauging is done by the Stueckelberg mechanism [84–87]. Using equilibrium conditions for the chemical potentials we calculate the ratio  $n_{DM}/n_B$  and then one has  $\frac{\Omega_{DM}}{\Omega_B} = \frac{m_{DM}n_{DM}}{m_B n_B} = 4.99 \pm 0.20$  which is satisfied for  $m_{DM} \leq 20$  GeV for a variety of

models. The main constraint on the model arises from  $g_\mu - 2$ . As mentioned already an important element in achieving a successful model of asymmetric dark matter is to have an efficient mechanism for the annihilation of its symmetric component. This is achieved in the proposed model by resonant annihilation via the Breit-Wigner  $Z'$  pole. [88, 89]. The  $Z'$  does not couple with the first generation leptons nor with the quarks, and couples only with the second and third generation leptons. Thus the usual LEP constraints on the ratio  $M_{Z'}/g$  do not apply to the  $Z'$  we consider and consequently the  $Z'$  here can have a mass close to twice the mass of the dark matter particle and a rapid annihilation of the symmetric component of dark matter can occur. A direct extension of the above mechanism can also be carried out for the supersymmetric case [82]. Here, however, a new feature arises in that in addition to the asymmetric dark matter one also has another candidate for dark matter, i.e., the neutralino and thus one has a two component dark matter picture. In order for the asymmetric dark matter mechanism to work one must deplete the neutralino component so that it is no more than, say one tenth of the asymmetric dark matter component. This was accomplished in [82]. Now the asymmetric dark matter is not observable in direct detection experiments because it has no direct interaction with quarks. It is then interesting to ask if the suppressed neutralino component may be measurable in experiment. Indeed the analysis given in [82] shows that even a subdominant neutralino will be accessible in future direct detection experiments such as future XENON-1T [77] and superCDMS [78] experiments.

### 3 Conclusion

The  $SO(10)$  model continues to be an attractive framework for unification. However, in  $SO(10)$  model building one is faced with many choices for the Higgs fields. Thus typically more than one representation is needed to break the GUT symmetry which makes the model less predictive as one needs additional assumptions on the VEVs of the Higgs fields to explain gauge coupling unification. This issue is resolved in models using higher Higgs representations such as  $144 + \overline{144}$  or  $560 + \overline{560}$ . Further, the latter model anchored in  $560 + \overline{560}$  also gives a natural doublet-triplet splitting via the missing partner mechanism. The GUT group embedded in supergravity, i.e., supergravity grand unification, allows one to make contact between GUT physics and low energy physics. Specifically the SUGRA GUT model predicts the light Higgs boson mass to be below  $\sim 130$  GeV. In this context the recent LHC data on the Higgs boson is very encouraging. The experimental data gives a hint of the light Higgs boson mass in the region around 125 GeV. Further, the analysis within mSUGRA indicates that a Higgs boson in this mass range requires sparticles to be generally heavy. It is found that most of the parameter space of models lies on the Hyperbolic Branch [41, 42] of radiative breaking of the electroweak symmetry and specifically on Focal Surfaces [45]. However, several sparticles could still be relatively light including the light stop and the light sbottom, as well as the charginos and neutralinos while the gluino mass can still lie below 1 TeV. More data expected from the LHC in the coming months will provide further tests of SUGRA GUTs. Thus LHC is an important laboratory for the test of both SUSY and GUTS and more specifically of the SUGRA GUT model.

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